

## CONVERSION OF WASTE POLYMERS TO ENERGY PRODUCTS

P. Assawaweroonhakarn, Z. Fan, J.L. Kuester  
Dept. of Chemical, Bio & Materials Engineering  
Arizona State University  
Tempe, Arizona 85287-6006

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### ABSTRACT

A project was performed to determine the feasibility of converting waste polymers into diesel fuel. The primary waste polymer source of interest was disposable diapers, consisting of a mixture of cellulosic and synthetic polymer material in the presence of biological wastes. The overall project consisted of five phases: (1) reaction equilibrium calculations, (2) batch pyrolysis study, (3) continuous pyrolysis study, (4) continuous liquefaction study, and (5) integrated system demonstration. The integrated system consists of a circulating solid fluidized bed pyrolysis system to produce a synthesis gas for a fluidized bed catalytic liquefaction reactor. The objective for the pyrolysis system is to optimize the composition of hydrogen, carbon monoxide and ethylene in the synthesis gas for conversion to diesel fuel in the catalytic liquefaction reactor. The liquefaction reactor produces a product very similar to commercial No. 2 diesel fuel.

### INTRODUCTION

Approximately 18% by volume of municipal solid waste consists of waste plastics (1). The 15.8 billion disposable diapers used annually comprise about 2% of the total waste stream. Due to increasing landfill costs and environmental and regulatory pressure, a flurry of activity has emerged to seek alternatives to landfill disposal of these materials. Proctor & Gamble, for example, has announced an "accelerated composting" program for their disposable diaper products (2). Separation steps are implemented to segregate the non-compostable parts from the cellulosic parts. The intent is to convert the cellulosic parts into "soil enhancer" (compost). Presumably, the plastics part still goes to the landfill. The questions would be the market for the "soil enhancer" and the probable necessity to still landfill the plastics. An alternative approach would be to convert the bulk diaper (all components) into marketable products with minimal landfill requirements. This approach has been developed at Arizona State University (ASU) utilizing over 100 different feedstocks, generally falling into the categories

of industrial wastes, municipal wastes, hazardous wastes and various agricultural and forest residues. An indirect liquefaction approach is used, i.e., gasification of the feed material to a gas followed by liquefaction of the gas to a No. 2 diesel grade transportation fuel. The sequence is illustrated in Figure 1. The objective in the gasification step is to maximize the production of hydrogen, carbon monoxide and ethylene while the objective in the second step is to maximize the production of diesel fuel from these three reactants. A high octane product can be produced via conventional catalytic reforming of the diesel material. The potential products are thus liquid hydrocarbon fuels, medium quality gas (ca. 500 BTU/SCF) and/or electricity (via heat recovery or combustion of the fuels). Alternative operating conditions and catalysts for the second stage reactor could produce other products (e.g., alcohols, methane etc.).

Prior work on this process has been described elsewhere (see, for example, references 3-6). This paper will present the application for disposable diapers. A five phase approach was used (reaction equilibrium calculations, batch pyrolysis study, continuous pyrolysis study, continuous liquefaction study, integrated system demonstration) with performance limited to an 11 month period. The intent was to minimize the project risks and costs for scale-up to a commercial configuration. Using the composition of a particular disposable diaper product ("Huggies") as an example, the maximum yields of diesel fuel (wet and dry basis) are illustrated in Figure 2. Realistic actual liquid product yields are expected to be in the 50-100 gals/ton range (dry basis).

## EQUILIBRIUM CALCULATIONS

Composition analysis for three commercial disposable diaper products is shown in Table 1. Since the compositions are similar, Huggies will be used for example calculations. Assuming a gas product slate of hydrogen, carbon monoxide, ethylene, ethane, acetylene, methane and carbon dioxide, the equilibrium product composition was calculated as a function of temperature by minimizing the Gibb's free energy of formation subject to atom balance constraints. Results are shown in Figure 3. As shown, all components decrease with temperature except hydrogen and carbon monoxide. The desired hydrogen/carbon monoxide ratio of ca. 1.2 (based on prior work) is achieved at ca. 1100 K (1550 F). No ethylene is predicted at equilibrium, as expected in the presence of hydrogen.

## BATCH PYROLYSIS STUDY

These experiments were performed in a Chemical Data Systems Model 122 Pyroprobe coupled to a Carle Gas Chromatograph Model AGC111H. The

Pyroprobe consists of a temperature programmed ampule containing a sample of the desired feedstock with product gas being swept to the gas chromatograph via helium carrier gas. A full factorial designed experiment was performed for the factors temperature and water composition. The experimental design is given in Figure 4 with the results shown in Table 2 using Huggies as the example feedstock. The base condition for temperature was set by results from the reaction equilibrium calculations. The three responses of interest are: (1) hydrogen + ethylene + carbon monoxide, (2) hydrogen/carbon monoxide, and (3) ethylene. The superior level for all three responses is at the high level for each factor (experiment E). The factor ranking (via analysis of variance calculations) and experimental error (as calculated by base point replication range divided by factorial experiment range) is shown in Table 3. All response results are considered to be favorable for further investigation in a continuous system.

#### CONTINUOUS PYROLYSIS STUDY

This task was performed in a reactor constructed from 3 inch schedule 40 pipe with a length of 3 feet. A fluidized bed configuration was utilized with electrical heating, a screw type solids feeder, overhead scrubber and recycle gas system via a compressor. Thus this phase was to be continuous with respect to feed and product withdrawal but batch with respect to the fluidized solid. Operating conditions for an experiment to study temperature effect on gas composition using a Huggies sample are shown in Table 4. The "steady state" conditions reported were determined by relatively stable periods of reactor temperature. Some problems were encountered in achieving consistent feed rates in this task. Gas composition results are shown in Table 5. The gas phase results are considered reasonable and favorable for liquid fuels production.

#### CONTINUOUS LIQUEFACTION STUDY,

A 2 inch fluidized bed reactor was used for this study (continuous gas feed, electrical heaters, cooling coils, continuous product withdrawal via a condenser and trap, catalytic noncirculating fluidized solid). The factors temperature, pressure and residence time were studied with regard to the responses of liquid product yields, bulk properties and yields. Gas feed was from cylinders based on the compositions achieved from the batch and continuous pyrolysis studies. A cobalt/alumina catalyst was used. Yields in the 20-30 gals/ton range were achieved in limited experimentation. These yields would be expected to improve substantially by implementing the following: (1) recycle of the off gas, (2) feed gas composition improvement, (3) catalyst improvement, and (4) liquefaction reactor optimization. Product quality information is provided in Table 6 as compared with commercial

materials. In general, this comparison indicates that the liquid fuel is a competitive product without any additional refining steps.

#### INTEGRATED SYSTEM DEMONSTRATION

This task was performed in an existing integrated system (Figure 5) consisting of a circulating solid fluidized bed gasification system followed by a fluidized bed catalytic liquefaction reactor. The intent was to run the system for an extended period of time at fixed operating conditions as determined by the previous tasks in order to report commercially realistic mass and energy balances for economic and scale-up studies. Unfortunately, this effort was hampered by lack of availability of a suitable solids feeder within the budgeted performance period. The problem is considered to be readily solvable with proper effort. Gasification composition data for a relatively stable period is shown in Figure 6.

#### SUMMARY AND CONCLUSIONS

The production of liquid hydrocarbon fuels from biologically contaminated disposable diapers is a technically viable concept. Favorable synthesis gas compositions can be produced. High quality liquid hydrocarbon fuel products can be produced from the synthesis gas. Additional research and development work is required to establish reliable mass and energy balances before scale-up is considered. To accomplish this objective, a reliable solids feeder system needs to be designed and tested. This is not considered to be a major obstacle.

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TABLE 1

Elemental Analysis of the Waste Polymer Samples.

COMPOUND	ELEMENT	SAMPLE 1 Huggies	SAMPLE 2 Lars	ANALYST SOURCE
Cellulose	carbon	1.2	1.2397	1.4417
	hydrogen	1.09	1.1073	1.2668
	oxygen	0.81	0.8145	0.8145
Polystyrene	carbon	0.31	0.2561	0.1841
	hydrogen	1.06	0.9794	0.7173
	oxygen	0.13	0.2142	0.2037
SAC	carbon	0.167	0.2338	0.2216
	hydrogen	0.107	0.1623	0.125
	oxygen	0.01	0.0142	0.0142
Polychloride	carbon	0.2	0.2338	0.285
	hydrogen	0.4	0.6716	0.668
	chlorine	0.108	0.1633	0.2143
Epoxyresin	carbon	0.143	0.2145	0.4952
	hydrogen	0.143	0.2145	0.4952
	oxygen	0.016	0.016	0
Urethane	carbon	0.0014	0	0
	hydrogen	0.0014	0	0
	nitrogen	0.0014	0	0
Urethane	carbon	10.71	10.71	10.72
	hydrogen	2.38	2.38	2.38
	nitrogen	0.5	0.5	0.5
TOTAL	carbon	2.2916	2.2674	2.1104
	hydrogen	12.6448	12.5118	12.425
	nitrogen	7.1101	7.1101	7.1101
TOTAL	carbon	0.011	0.0232	0
	hydrogen	0.011	0.0232	0.0297
	nitrogen	0.011	0.0232	0.0297

Unbalanced for glass	Carbon	Hydrogen	Nitrogen
Carbon	1.4	1.4	1.4
Hydrogen	0.31	0.23	0.23

Source: Kimberly-Clark Corporation.

TABLE 3

Analysis of Variance Calculation Results.

RESPONSE	FACTOR RANK	% ERROR
$H_1 + CO + C_2H_4$	Temperature, Water	9.6
$H_2CO$	Temperature, Water	9.8
$C_2H_4$	Water, Temperature	0

TABLE 2

Gas Compositions from Huggies  
(Factors: Temperature and Water Addition).

EXPERIMENT	A	B	C	D	E
OPERATING CONDITION					
COIL TEMPERATURE (°C)	1375	1469	1577	1377	1467
COIL TEMPERATURE (°F)	2503	2691	2871	2509	2673
REACTION TEMPERATURE (°C)	1095	1176	1255	1096	1173
REACTION TEMPERATURE (°F)	1993	2135	2291	1995	2113
WATER ADDED (WT %)	64.3	0	0	64.3	78.2
(WORKING wt sample)	0.14	0	0	0.14	0.36
WATER COMPOSITION (MOLE %)					
$H_2$	26	29	14.5	21	22
$CO_2$	19	19	34	16	20
$C_2H_4$	7	5	7	6	7
$C_2H_2$	3	1	3	3	3
$C_2H_6$	0	0.2	0	0	0
$CH_4$	13	11	10.8	14	14
$CO$	20	34	26.7	23	22
WATER RATIO	0.59	0.13	0.47	0.15	0.19

TABLE 4

Experimental Details

Reactor: material..... 316 stainless steel  
 diameter..... 1.5 in.  
 length..... 3 ft

Sample: Huggies & synthetic urine

Operating Conditions:  
 Pressure..... 3 psig  
 Flow rate..... 0.5 g/min  
 Feed rate..... 0.5 g/min  
 Solid type..... Alumina (80 mesh)  
 Solid loading..... 0.028 in.  
 Fluidizing gas..... Recycle pyrolysis gas

Factor: Temperature..... 1400°F, 1700°F

Reactant: Gas Composition

TABLE 5

Task 3: % gmole of Gas Product at "Steady" State

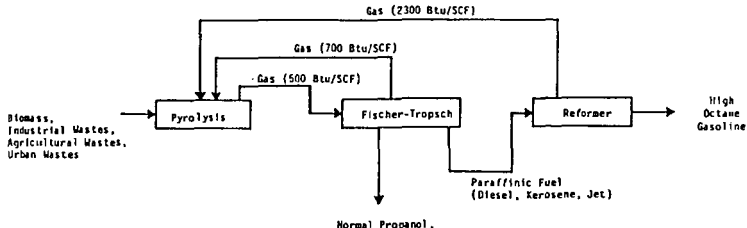
EXPERIMENT	A	B	C	D	E
Average Temperature (degree F)	1441.625	1532	1719.5	1658.5	1544
Range of time (min)	3.4	1.8	2.2	1.4	5
Hydrogen	34.05	34.71	56.72	48.74	39.54
Carbon dioxide	8.08	4.62	4.52	3.31	5.04
Ethylene	7.20	5.31	0.57	1.70	4.19
Ethane	1.27	0.97	0.20	0.22	1.28
Nitrogen	1.01	1.09	0.71	0.71	0.62
Methane	19.42	19.05	2.90	9.64	14.88
Carbon monoxide	27.97	34.25	34.81	35.68	34.08

TABLE 6

Properties of Fischer-Tropsch Product and Commercial Fuel Oils

	No. 2 Diesel	Kerosene	JP-4	Waste Polymers Feedstock
Specific Gravity	0.8360	0.8108	0.7588	0.7470
Gravity, API *	37.8	43	55	37.8
Boiling point range, °F				
10%	368	336	147	179
Evaporated at:				
50%	458	410	302	308
90%	563	478	438	526
Calculated cetane index	44.2	44.2	37.8	45.7
Heating value, BTU/lb.	19380	21978	22440	19058

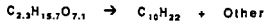
FIGURE 1



Basic Chemical Conversion Scheme

FIGURE 2

Huggies → Diesel



Composition (wt%)

	Huggies (wet)	Huggies (dry)	Diesel
C	17.54	53.44	84.51
H	9.97	7.64	15.49
O	71.82	37.19	0
N	0.02	0.04	0
Na	0.56	1.70	0

Maximum yield : 67 tons diesel  
(carbon balance) ton Huggies (wet)

189 tons diesel  
ton Huggies (dry)

FIGURE 3

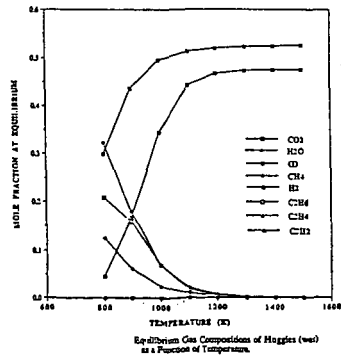


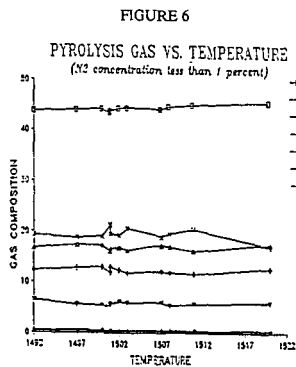
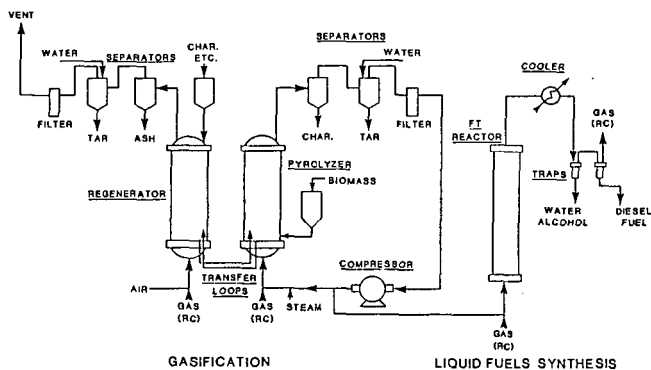
FIGURE 4

FACTOR	LEVEL		
	-1	0	+1
Temperature (K)	1019	1102	1185
Temperature (°F)	1375	1525	1675
Water (wt%)	0	64.3	78.3
( $\mu$ l/0.1 mg.)	0	0.18	0.36

PRESSURE: 1 atm  
RESIDENCE TIME: 20 seconds

Experimental Design for Huggies.

FIGURE 5  
CONVERSION SYSTEM SCHEMATIC





## **GASIFICATION OF WASTE PLASTICS FOR THE PRODUCTION OF FUEL-GRADE GAS**

Laura Sharp  
Robert O. Ness  
Energy and Environmental Research Center  
University of North Dakota  
Box 8213, University Station  
Grand Forks, ND 58202

Keywords: gasification, waste, fluid-bed reactor

### **INTRODUCTION**

Many areas of the United States are experiencing waste disposal problems stemming from both a shortage of landfill space and a public concern for the environmental impacts and the appearance of landfilling. Although it is still the cheapest method of disposal, the rising cost of landfilling is making energy from waste more economically feasible. Incineration, another popular waste disposal method, faces ever more stringent emissions regulations, making it an increasingly less attractive alternative economically. New gasification and pollution control technologies are making it possible for waste materials to be used as environmentally acceptable sources of energy. Two possible waste materials which might be used as a feedstock for energy production, ebonite and automotive shredder residue, are being investigated at the Energy and Environmental Research Center at the University of North Dakota.

Several tests have been conducted with ebonite in a thermogravimetric analyzer (TGA) and a 1 to 4-lb/hr continuous fluid-bed reactor (CFBR) using  $K_2CO_3$  and Paris limestone catalysts. Tests are scheduled for the automotive shredder residue. Data from the tests include carbon conversion, gas production, wastewater production, heavy metal analysis, and chlorine analysis. Analysis of the data includes discussion of the effects of the benefits of producing a fuel gas and the decrease in landfill volume, the environmental impacts of heavy metal disposal from the ash produced in the system, and the technological requirements for gas cleanup.

### **WASTE FEED MATERIAL**

Automotive shredder residue is a waste product generated in the dismantling of automobiles. After removal of the gas tank and battery, the automobile is shredded to provide a material approximately less than 4 inches in size and composed of approximately 50% organic and 50% inorganic fractions. Magnetic separation is then used to separate out ferrous scrap. Air cyclone separators isolate a low density "fluff" from the nonferrous fraction (aluminum, copper, etc.). This fluff (shredder residue) is composed of a variety of plastics, fabrics, foams, glass, rubber, and an assortment of contaminants. This waste product contains a wide variety of heavy metals and halogens, making it an excellent test material, as it will present many of the common problems to be considered when using waste as a gasification feedstock. Tests on automotive shredder residue are scheduled in the TGA and in the 1 to 4-lb/hr CFBR to investigate its gasification potential.

Ebonite, a hard rubber material used primarily in car battery casings, was tested both in a TGA and in the CFBR. Three tests in the TGA included one test at 800°C, with potassium carbonate as a catalyst, and two tests at 900°C, one of these with potassium carbonate and one with Paris limestone. The tests in the 1 to 4-lb/hr CFBR were all carried out using potassium carbonate as a catalyst, since it accelerated the process to the greatest degree. Table 1 shows the proximate and ultimate analyses of the ebonite.

## EBONITE TGA GASIFICATION TESTS

Tests were conducted in the thermogravimetric analysis (TGA) instrument to determine test matrix conditions for further experiments to be run in the 1 to 4-lb/hr bench-scale unit. Ebonite reactivity with steam and two catalysts were investigated at temperatures of 800° and 900°C (Figure 1-4).

In all tests, the reactant mixtures containing -60-mesh ebonite were heated to the desired reaction temperature and held at temperature until approximately half of the fixed carbon in the sample had been converted to gas, at which point the reaction was terminated by cutting off the steam and heat supply. A -60-mesh ebonite was used due to the difficulty in obtaining samples of reproducible size distribution from the bulk samples. The +60-mesh-size fraction had the same TGA proximate analysis as the -60-mesh fraction, implying the difference (if any) in their reactivities would likely not be chemical, but due to a difference in surface area. All tests were performed under flowing argon gas.

To determine the point at which half of the fixed carbon had been converted, TGA proximate analyses were carried out on each sample prior to the reactivity tests. These analyses (Table 2) showed that volatiles are removed from the reactant mixtures, and the remaining material consists of about 63% fixed carbon and 37% ash for ebonite with catalyst and about 76% fixed carbon and 23% ash for ebonite without catalyst.

The TGA graphs start at time = 0. This point marks the beginning of the heat-up period. Weight loss during the heat-up period (as measured by a decreasing weight percent value) is due to moisture loss and devolatilization. When the reaction temperature is achieved (at which point devolatilization is essentially complete), the weight percent value is manually reset to a y-value of 100%, and steam is added. When 50% of the fixed carbon is converted, heat is turned off and the steam flow terminated. The point at which 50% of the fixed carbon is converted is determined by examination of proximate analysis data. As stated, each reactivity test was terminated when about half of each devolatilized sample had been converted to gas: 31.5 weight percent of the sample in the case with catalyst and 38.1 wt% of the sample in the case with no catalyst. After the termination of heat and steam, the conversion line still continued until the instrument was turned off, since some residual steam was still present, but it was not linear.

The catalysts investigated were Paris limestone (calcium carbonate) and potassium carbonate. All catalyst tests were performed using mixtures of ebonite and 10 weight percent-added catalyst. The ebonite/limestone test was performed at 900°C, and ebonite/potassium carbonate tests were performed at 800° and 900°C. The TGA data indicated that Paris limestone had a minor effect on the reactivity of the ebonite at 900°C (Figure 2), compared with the reactivity of ebonite without catalyst at the same temperature (Figure 1). Potassium carbonate, however, significantly affected reactivity. Conversion at 800°C (Figure 3) and at 900°C (Figure 4) with a potassium carbonate catalyst occurred quite rapidly. The residence time required for complete conversion at 800°C is 5.5 minutes and at 900°C is 2 minutes, whereas conversion time at 900°C is 18 minutes. Residence times for 50% and 100% conversion were found graphically. The point for 100% conversion was found by extrapolating the linear portion of the conversion line. The reaction appears to be zeroth order with respect to carbon. As conversion approaches 100%, the reaction is no longer strictly zeroth order because unreactable material (ash) limits access to carbon, but the order goes up only to approximately 0.2, introducing a very small error into the calculated time for total conversion.

## EBONITE CFBR GASIFICATION TESTS

Bench-scale testing was performed in a 1 to 4-lb/hr fluid-bed reactor system, shown in Figure 5. Preheated gas and steam are introduced into the bottom of a 3-inch-

diameter reactor. The lower section of the reactor, which is attached to the coal feed system, is made of 3-inch pipe and is 33 inches in length. The freeboard section is made of 4-inch pipe, 18.75 inches in length. Solids remain in the bed until, through weight loss from gasification, they reach the top of the 3-inch section and fall out through the top bed drain leg, where they are collected in an accumulation vessel. Unreacted fines and some ash particles are entrained and separated from the gas stream by a 3-inch cyclone. Liquids are condensed in one of two parallel indirect cooled condensation trains. Gas is then metered and sampled by an on-line mass spectrometer.

The particle-size distribution of the ebonite was determined by sieve analysis; the results of which are shown in Table 3. Cold flow fluidization tests indicated a well-fluidized bed at 0.6 to 0.8 ft/s.

Carbon conversion for the ebonite was found to be approximately 90% at 900°C, with most of the unreacted ebonite found in the condensation train, indicating that fines blew out of the bed before having sufficient residence time for complete conversion. A narrower particle size for the feed, a lower fluidization velocity, or a larger diameter freeboard section would most likely raise this conversion by reducing fines entrainment. Alternatively, a reactor/cyclone recycle system that is designed for this particular feedstock would also produce higher conversions. Comparing the amount of material in the bed with the feed rate indicates that the residence time for the test was less than 1 hour. The residence time is extremely dependent on temperature and heat-up rate. Ebonite agglomerates at temperatures below about 800°C. If the reactor is not above 850°C and at a high heat-up rate, the ebonite will agglomerate, and the reaction rate and overall conversion are greatly reduced.

Gas produced from gasification and from water-gas shift reactions is between 220 to 280 lbs per 100 lbs of MAF ebonite feed material. Average composition of the product gas is shown in Table 4. Gas produced has a Btu content of approximately 260 Btu/scf. This number does not include nitrogen used in fluidization.

Water conversion was found to be 1.5-2.0 mole water/mole fixed carbon based on material balance data. Trace-element analysis showed considerable loss of lead from the ebonite, going from 660 ppm in the feed to 257 ppm in the product char. Antimony also decreased considerably, starting off at 696 ppm and ending up at 129 ppm. Chlorine content went from 160 ppm to 149 ppm.

#### ENVIRONMENTAL IMPACTS OF GASIFYING WASTE MATERIAL

Gasification of ebonite offers not only the benefit of energy production, but also decreases waste volume that needs to be landfilled. Density of the feed material (ebonite) is approximately 0.73 g/mL. Density of the reacted material (top bed drain) is approximately 0.56 g/mL. On an as-received basis, 12.8 ft<sup>3</sup> out of 100 ft<sup>3</sup> fed will be left over for landfill (assuming the 90% conversion). If 100% conversion is achieved, 14.5 grams per 100 grams of feed will be left over to landfill, resulting in a volume decrease of 87%.

Wastewater from the process may contain some heavy metals, including lead and antimony. Acid leaching the ebonite prior to gasification would be desirable to eliminate as much of the heavy metals as possible in downstream operations. Additionally, leachability studies will need to be conducted on the unconverted material. Gas cleanup problems will include the need to eliminate sulfur- and chlorine-containing compounds such as H<sub>2</sub>S and HCl from the gas stream, as well as trace metals that may vaporize and recondense as particulates. The ebonite feed material is fairly high in sulfur, having an as-received sulfur content of 3.9%.

## FUTURE TESTS

Further tests are planned to determine:

- the yield structure for automotive shredder residue and to verify the yield structure for ebonite
- optimal fluidization velocity
- carbon conversion with reduced fluidization velocity
- the effect of steam to carbon ratio
- the effect of increased pressure on gas yields
- the fate of vaporized heavy metals
- methods of ash stabilization
- the feasibility hot-gas cleanup
- leachability properties of unreacted material

Two of the key reactor design parameters that need further investigation include the fluidization velocity and the steam to carbon ratio. Carbon conversion could be increased if the fines could be kept in the reactor. The steam to carbon ratio coupled with the reactor pressure could change the output of carbon monoxide and hydrogen produced in the system. The heavy metals that are vaporized will either condense in the condensate train, which will cause scaling over a long period of time, or possibly recondense as particulates in the gas stream. More information will be needed on where these metals condense in order to determine the best way to deal with them.

## SUMMARY

The future of waste disposal appears to be moving away from landfilling and incineration and toward recycling and using waste materials as a source of energy. New technology in pollution control and in energy generation techniques, such as gasification, make energy production from waste materials an environmentally acceptable alternative. Testing on ebonite, a hard rubber waste material, indicates that a high Btu gas can be produced in a reasonable residence time. Some work remains to be done to optimize operating conditions and to determine how to deal best with heavy metals and chlorine and sulfur compounds.

## REFERENCES

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TABLE 1

## EBONITE ANALYSIS

	<u>As Det.</u>	<u>As-Received</u>	<u>MF</u>	<u>MAF</u>
<u>Proximate</u>				
Moisture	1.98	2.00	N/A	N/A
Volatile Matter	37.1	37.1	37.85	44.4
Fixed Carbon	46.45	46.43	47.39	55.59
Ash	14.46	14.46	14.73	N/A
<u>Ultimate</u>				
Hydrogen	4.82	4.82	4.69	5.5
Carbon	70.34	70.34	71.76	84.18
Nitrogen	1.12	1.12	1.14	1.34
Sulfur	3.91	3.91	3.99	4.68
Oxygen	5.34	5.34	3.65	4.28
Ash	14.46	14.46	14.76	N/A

TABLE 2

## PROXIMATE ANALYSES OF EBNITE/CATALYST MIXTURES

	<u>Ebonite/10% CaCO<sub>3</sub></u>	<u>Ebonite/10% K<sub>2</sub>CO<sub>3</sub></u>
Moisture	1.70	2.76
Volatile Matter	36.53	36.97
Fixed Carbon	39.77	37.64
Ash	22.00	22.66

TABLE 3

## EBONITE PARTICLE-SIZE DISTRIBUTION

<u>Tyler Mesh Size</u>	<u>Weight Percent Retained</u>
4	1.38
6	8.01
8	15.73
20	31.00
60	21.32
325	14.79
-325	7.71

TABLE 4

GAS ANALYSIS<sup>1</sup>

H <sub>2</sub>	50.1
CO <sub>2</sub>	28.8
H <sub>2</sub> S	0.9
CH <sub>4</sub>	4.5
CO	15.0

<sup>1</sup> Without nitrogen fluidizing gas.

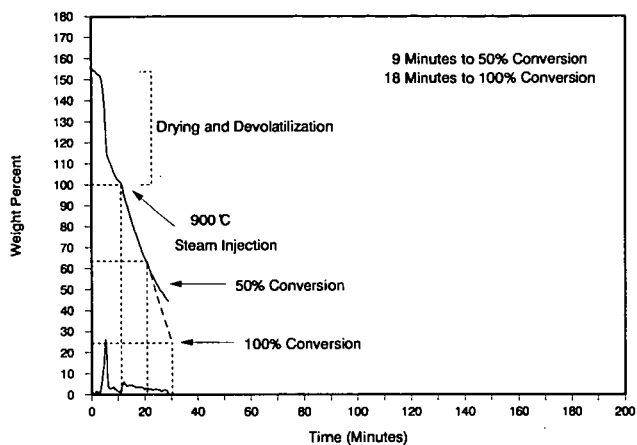


Figure 1. Steam reactivity of ebonite at 900°C.

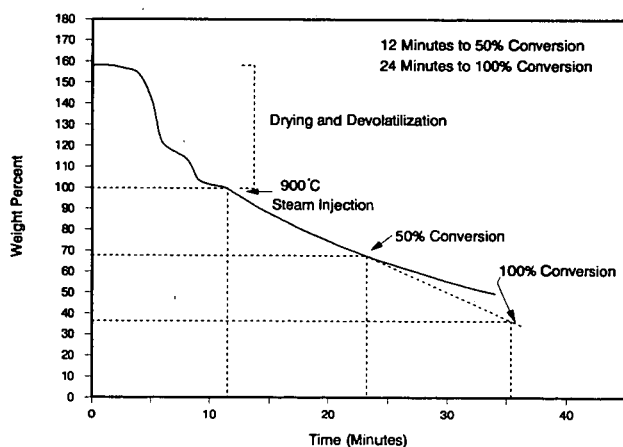


Figure 2. Steam reactivity of ebonite and calcium carbonate catalyst at 900°C.

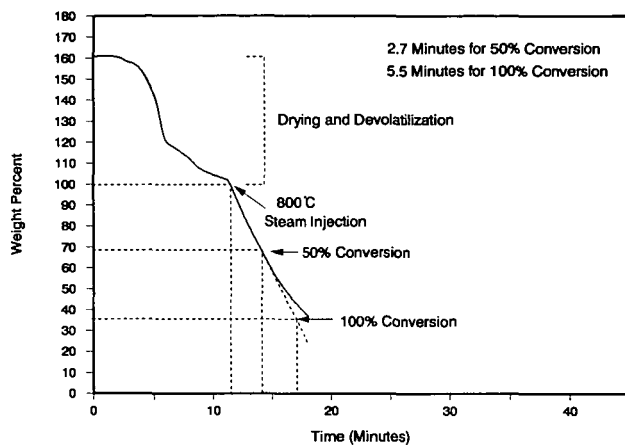


Figure 3. Steam reactivity of ebonite and potassium carbonate catalyst at 800°C.

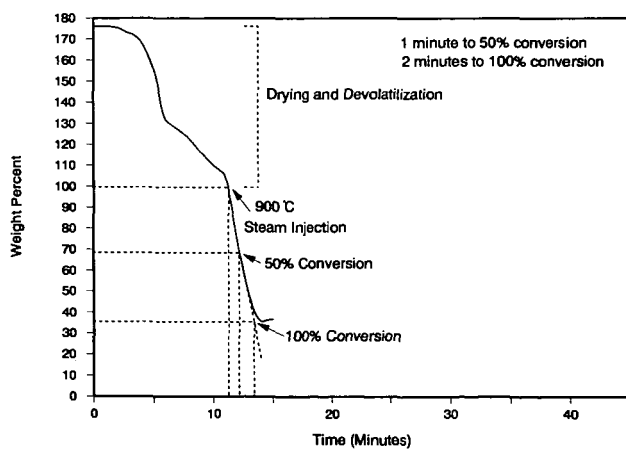


Figure 4. Steam reactivity of ebonite and potassium carbonate catalyst at 900°C.

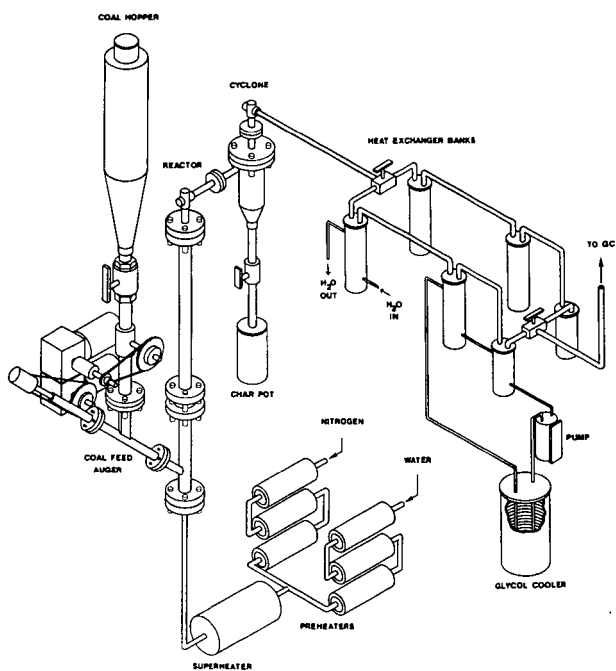


Figure 5. 1-4 lb/hr CFBR schematic.



## RECOVERY OF ENERGY FROM MSW

M. D. Ackerson  
E. C. Clausen  
J. L. Gaddy  
Department of Chemical Engineering  
University of Arkansas  
Fayetteville, AR 72701

### ABSTRACT

Methods for disposal of MSW that reduce the potential for groundwater or air pollution will be essential in the near future. Seventy percent of MSW consists of paper, food waste, yard waste, wood and textiles. These lignocellulosic components may be hydrolyzed to sugars with mineral acids and the sugars may be subsequently fermented to ethanol or other industrial chemicals. This paper presents data on the hydrolysis of the lignocellulosic fraction of MSW with concentrated HCl and the fermentation of the sugars to ethanol. Yields, kinetics and rates are presented and discussed. Design and economic projections for a commercial facility to produce 20 MM gallons of ethanol per year are developed. Novel concepts to enhance the economics are discussed.

### INTRODUCTION

The United States generates about 200 million tons of MSW annually, or about 4 pounds per capita per day (US EPA, 1981). The average composition of MSW is given in Table 1, and varies slightly with the season (Ng, *et al.*, 1983). This material has traditionally been disposed of in landfills. However, recent environmental concerns over groundwater pollution, leaching into waterways, and even air pollution, as well as increasing costs, have resulted in this technology becoming unacceptable in most areas. Few new landfills are being approved and the average remaining life of operating landfills is only about five years.

Alternatives to landfilling include incineration, composting, anaerobic digestion, and recycling. Incineration can result in energy recovery as steam. However, concerns over hazardous components in exhaust gases and high capital and operating costs detract from this alternative. Large areas required for composting and the ultimate use or disposal of compost with high metals content makes this technology uncertain. Very slow reaction rates and large reactors for anaerobic digestion makes this technology uneconomical at present.

Recycling of glass, metals, plastics, and paper reduces the quantity of material to be landfilled by about 60 percent, as seen from Table 1. Most states have decided that recycling offers the best solution to the environmental concerns associated with solid waste disposal and many have implemented regulations for curbside segregation of recyclable components. Markets for recycled aluminum and steel are well established, however, markets for recycled paper, glass, and plastics are not well developed. Low prices (negative in some areas for paper) will impede the application of recycling.

#### Alcohol Production

The United States currently imports about half of its crude oil and must produce another 120 billion gallons of liquid fuels annually to become energy self sufficient. Ethanol can be produced from lignocellulosic matter, like paper, by hydrolysis of the polysaccharides to sugars, which can be fermented into ethanol. This technology would enable the use of the entire carbohydrate fraction of MSW (paper, yard and food waste, wood and textiles), which consti-

tutes 75 percent of the total, into a useful and valuable product. Ethanol can be blended with gasoline and, currently, nearly one billion gallons of ethanol, primarily made from corn, are used as a transportation fuel in this country. The potential market (at 10 percent alcohol) is 10 billion gallons per year. Blending of ethanol with gasoline reduces emissions and increases the octane rating. Some states, like California and Colorado where air quality has degraded seriously in metropolitan areas, are mandating the use of alcohol fuels.

The purpose of this paper is to describe a process for converting the lignocellulosic fraction of MSW into ethanol. The residue is contacted with concentrated mineral acid at room temperature to give theoretical yields of monomeric sugars, which are readily fermented into ethanol. Procedures to give high sugar concentrations are described. Data for fermentation in immobilized cell columns in a few minutes are presented. The economics of this process is then developed and key economic parameters identified.

#### HYDROLYSIS/ETHANOL PRODUCTION

The hydrolysis of biomass to sugars and fermentation of glucose to ethanol are technologies that have been commercial around the world for many years. The U. S. produced up to 600 million gallons of ethanol per year by fermentation during World War II. Also, the Germans produced fuel ethanol from wood by hydrolysis and fermentation during World War II. Today, Brazil produces most of its liquid fuel from sugar cane.

#### Hydrolysis Technology

Biomass materials are comprised of three major components: hemicellulose, cellulose, and lignin. The composition of various biomass materials is shown in Table 2. As noted, most of these materials contain 50-70 percent carbohydrate (hemicellulose and cellulose). These polysaccharides can be hydrolyzed to monomeric sugars, which can be converted by microorganisms into fuels or chemicals. The lignin cannot be hydrolyzed, but has a high heating value and can be used as a source of fuel. From Table 2, it is noted that most of the MSW biomass is cellulose.

The carbohydrate hydrolysis can be carried out by contact with cellulase or xylanase enzymes, or by treatment with mineral acids. Enzymatic hydrolysis has the advantage of operating at mild conditions and producing a high-quality sugar product. However, the enzymatic reactions are quite slow (30 hour retention time), and the biomass must be pretreated with caustic or acid to improve the yields and kinetics. The expense of pretreatment and enzyme production, and the large reactors required make this an uneconomical alternative.

Acid hydrolysis is a much more rapid reaction and various combinations of temperature and acid concentration may be used. Two methods of acid hydrolysis have been studied and developed: a high temperature, dilute acid process (Grethlien and Converse, 1982; Rugg, 1982) and a low temperature, concentrated acid process (Clausen and Gaddy, 1983; 1985). For example, complete conversion of the hemicellulose and cellulose in corn stover into monomeric sugars requires mineral acid concentrations of 2N at temperatures of 100-200°C (Clausen and Gaddy, 1982). However, acid concentrations of 10-14N yield complete conversions at room temperature (30°C).

At high temperatures, xylose degrades to furfural and glucose degrades to 5-hydroxymethyl furfural (HMF), which are both toxic to micro-organisms. Yields from dilute acid processes are typically only 50-60 percent of theoretical because of sugar losses by degradation and reverse polymerization at high temperatures. Also, equipment corrosion at high temperatures is a serious problem. Work in our laboratories has focused attention on concentrated acid

processes which produce theoretical yields at low temperatures. However, since high acid concentrations are used, acid recovery is an economic necessity (Clausen and Gaddy, 1983).

Studies in our laboratories have resulted in both single step and two-step hydrolysis processes, using concentrated mineral acids, which result in nearly 100 percent yields of sugars from hemicellulose and cellulose. The reactions are conducted at room temperature, without significant degradation or reverse polymerization (Prieto, *et al.*, 1988a; Clausen and Gaddy, 1985). An acid recovery process has been developed and tested, yielding an energy efficient method of separating sugar and acid (Clausen and Gaddy, 1987). The resulting sugar solution has been successfully fermented to ethanol and other chemicals without pretreatment (Prieto, *et al.*, 1988b).

Process Description. Figure 1 shows the proposed process for the acid hydrolysis of MSW, consisting simply of a mixed reactor where acid and MSW are contacted at a constant temperature. The unconverted solids (lignin and ash) are separated by filtration, washed, and used as fuel. Acid and sugars are separated and the acid returned to the reactor.

If desirable to separate the sugars, the hemicellulose, which degrades at milder conditions, may be first hydrolyzed to produce a mixture of five and six carbon sugars. The solids from this first stage reactor are separated and contacted with acid in a second step to hydrolyze the cellulose. Only six carbon sugars are obtained from cellulose in this second stage. This two step hydrolysis gives two streams; a xylose rich prehydrolyzate and a glucose rich hydrolyzate; and may be used where sugar separation is desirable. In the usual case, as with MSW, the simpler single step process will be preferred.

Hydrolysis Conditions. The two major factors which control the hydrolysis reactions are temperature and acid concentration. Studies in our laboratories have been made to define the appropriate conditions to maximize reaction rates and yields. Sugar degradation is promoted more at high temperature than at high acid concentration. Also, fast rates of hydrolysis are achieved at acid concentrations exceeding 12N. Therefore, the best conditions are a high acid concentration (80 percent  $H_2SO_4$  or 41 percent HCl) and a mild temperature ( $-40^{\circ}C$ ).

The sugar concentrations and yields from a typical hydrolysis of MSW from our laboratories are given in Table 3 (Clausen and Gaddy, 1985). The prehydrolysis step yields 8 percent of the initial MSW as xylose. The combined yield of glucose is 60 percent. These yields represent nearly complete conversion of hemicellulose and cellulose to sugars. However, very dilute (3-7 percent) sugar solutions result from these reactions.

#### Hydrolyzate Fermentation/Ethanol Production.

Glucose may be fermented to ethanol efficiently by the yeast *Saccharomyces cerevisiae*, or the bacterium *Zymomonas mobilis* (Waldron *et al.*, 1988). Batch fermentation experiments were carried out to compare the production rates of ethanol from hydrolyzates and synthetic glucose. *Saccharomyces cerevisiae* (ATCC 24860) was used in the study. Identical results were found when fermenting synthetic glucose and hydrolyzate. Ethanol yields were also nearly identical. As noted in Table 4, the fermentation proceeded well in the presence of a small amount (0.25 percent) yeast extract, which can be obtained by recycle. Almost total conversion of sugars is obtained in only 16 hours. The concentrations of furfural and HMF in the hydrolyzates were found to be negligible. These low levels of by-products are believed to be the major reason for this highly efficient fermentation.

Xylose fermentation is much more difficult and the xylose might be used as a

source of energy for generating steam and power. However, future possibilities for xylose fermentation will improve the economics. Recent work with Pachysolen tannophilus shows promise for xylose conversion to ethanol (Schneider et al., 1981) but, at present, this technology is not fully developed. Ethanol may also be produced by converting xylose to xylulose, followed by fermentation with yeast (Gong, et al., 1981).

Continuous Fermentation. The standard technology for fermenting sugars to ethanol is in batch vessels. Batch fermentation is used so that contamination and mutation can be controlled. Sterilization between batches and the use of a fresh inoculum insure efficient fermentation. However, most batch alcohol fermentations are designed for thirty hour (or more) reaction time, which results in very large and expensive reactors.

The reactor size can be reduced substantially by using continuous flow fermenters. When fermenting acid hydrolyzates, the problems with maintaining sterile conditions are substantially reduced, since the substrate has been sterilized by contact with the acid. Therefore, the use of continuous fermentation is a natural application for producing alcohol from MSW hydrolyzates.

A number of continuous fermentation schemes have been studied, including the CSTR (Cysewski and Wilke, 1978), cell recycle reactor (Elias, 1979), flash fermentation (Cysewski and Wilke, 1977), and immobilized cell reactors (Sitton and Gaddy, 1980; Vega et al., 1988). Immobilized cell reactors (ICR) show potential in substantially decreasing reactor size and decreasing substrate and product inhibition (Vega et al., 1988; Gainer et al., 1981; Linko, 1981; Rowe and Margaritis, 1981). Reaction rates for ethanol production in an immobilized cell reactor are as high as 10 times the values obtained in a stirred tank reactor (Sitton and Gaddy, 1980). A wide variety of immobilization techniques have been employed, including cross-linking, entrapment, and covalent bonding (Vega et al., 1988).

Data are given in Figure 2 for laboratory columns with immobilized S. cerevisiae. The glucose profiles are given for initial sugar concentrations from 50-200 g/L. As noted, 90 percent conversion is achieved in one hour or less. Productivities to achieve 99 percent conversion were about 40 g/L-hr, or about an order of magnitude greater than the CSTR and 60 times more than the batch reactor. Furthermore, alcohol inhibition and toxicity to other inhibitors are reduced in the ICR. The reactor volume of the ICR for MSW hydrolyzate fermentation is about 5 percent that of the batch fermenter and substantial capital savings result.

#### Increasing the Sugar Concentration

Perhaps the single most important factor in the economics of this process is the sugar concentration that results from acid hydrolysis. Dilute concentrations increase both the equipment size and the energy required for purification. Methods to increase the sugar and ethanol concentrations have been developed.

Solids Concentration. The ultimate sugar and alcohol concentrations are direct functions of the initial solids concentration in the hydrolysis. Since fluidity in a stirred reactor is a requirement, a 10 percent mixture has been considered maximum. Therefore, the resultant sugar concentrations have been only 2-7 percent and alcohol concentrations only half as much.

If the limiting factor is considered to be fluidity in the reactor instead of the feed mixture, the feed concentration could be increased by roughly the reciprocal of one minus the solids conversion in the reactor. Of course, solids and liquid would have to be fed separately, which could also save equipment

cost. For biomass, containing 75 percent carbohydrate, the reactor size could be reduced to one-fourth the size with a ten percent feed concentration. Attendant reductions would also result in the filtration and washing units.

Equally important are the resultant increases in sugar concentrations. The glucose concentration would be quadrupled to about 280 g/L (28 percent). Energy and equipment costs in the fermentation area would be reduced proportionately. This simple alteration in the process has a profound impact on the economics. It is estimated that the capital cost is reduced by 40 percent in the hydrolysis and acid recovery sections and 60 percent in the fermentation and utilities areas. Furthermore, the energy requirements for distillation are reduced by 60 percent.

Acid Recycle. Another method to increase the sugar concentration is to recycle a portion of the filtrate (acid and sugar solution) in the hydrolysis step. The acid would catalyze further polysaccharide hydrolysis to increase the sugar concentration. Of course, recycle of the sugars would also increase the possible degradation to furfural and HMF.

Experiments have been conducted to determine the enhancement possible with acid recycle. Various amounts of the acid and sugar solution from the filtration were recycled to determine the resulting sugar and by-product concentrations. Acid and solids concentrations and temperatures were kept constant. These experiments have shown that the sugar concentrations can be increased sixfold at total recycle. It should be noted that not all the filtrate can be recycled, since a portion adheres to the solids in filtration. In order to minimize sugar decomposition, a recycle fraction of 50 percent has been used, which results in doubling the sugar composition, without significant furfural or HMF levels.

The effect of acid recycle on the economics is significant. A recycle rate of 50 percent, coupled with high solids concentrations, would result in a xylose concentration of 15 percent and a glucose concentration of over 50 percent could be achieved. Practically, sugar concentrations should not exceed 25 percent, so a smaller recycle fraction is required. It should be noted that these concentrations have been achieved in the laboratory, while maintaining furfural and HMF less than 0.05 percent. These high concentrations reduce the equipment size in the acid recovery section by 50 percent and in the fermentation section by another 60 percent. Energy consumption is also reduced another 60 percent.

Acid Recovery. Acid recovery is essential when using concentrated acid hydrolysis. Processes for recovery of both hydrochloric and sulfuric acids have been developed. A number of possible recovery schemes were examined, including electrodialysis, distillation, etc.

The recovery technology that has been selected is based upon solvent extraction. Solvents have been identified that extract HCl and H<sub>2</sub>SO<sub>4</sub> from the aqueous sugar solutions. Near complete acid recovery is possible and solvent losses are minimized. For HCl, the acid is separated from the solvent by distillation, and the solvent recycled. A hexane wash of the sugar solution is used to recover trace quantities of solvent, and hexane is separated by distillation for recycle.

Some solvent is lost in the process; however, the losses are quite small and solvent replacement costs are only \$0.02 per gallon of alcohol. Acid losses are minimized and acid costs are \$0.025 per gallon of alcohol. The total heat requirement for solvent and acid recovery is low and amounts to less than \$0.05 per gallon of alcohol. As shown later, the energy cost may be recovered from the lignin and xylose streams.

## ECONOMIC PROJECTIONS

To illustrate the economics of this process, a design has been performed for a facility to convert MSW into 20 million gallons per year of ethanol, utilizing the acid hydrolysis procedures previously described. The capital and operating costs are summarized in Table 5.

MSW would be collected and delivered to the plant site as needed. Feedstock preparation consists of plastic, metal and glass removal, shredding, grinding and conveying to the reactors. The cost of the removal of glass and metals is not included in the feed processing cost, as reports indicate that resale of these materials will offset the capital and operating costs of separation. The hydrolysis section, as shown in Figure 1, consists of continuous reactors. Acid resistant materials of construction are necessary for this equipment. Ethanol fermentation in the ICR and typical distillation units are included. The total capital cost for this plant is \$35 million, including all utilities, storage and offsites.

The annual operating costs are also shown in Table 5. These costs are also given on the basis of unit production of alcohol. As mentioned previously, no cost is included for MSW. A lignin boiler is used to reduce the energy requirements, and energy costs are only \$0.08 per gallon. Fixed charges are computed as a percentage of the capital investment and total \$5.6 million per year. The present ethanol price of \$1.50 per gallon will yield a pre-tax profit of \$18.5 per year (\$.93/gal) or 53 percent per year.

It should be noted that this process does not include utilization of the pentose stream. Acid recovery is included, but fermentation of the xylose is not provided. Xylose could be fermented to alcohol, acids or other valuable chemicals, which would improve the economics. However, since this technology is not perfected, such products have not been included.

Sensitivity analyses show that the economics are particularly sensitive to capital cost and revenue. A 20 percent reduction in capital cost raises the pre-tax return to 70 percent. Similarly, a 20 percent increase in the ethanol price increases the return to 70 percent. A tipping fee of \$20 per ton of MSW would increase the return to 65 percent. Increasing the plant size would have a similar positive affect on the economics.

## CONCLUSIONS

Concentrated acid hydrolysis of residues, such as MSW, requires mild temperatures and results in near theoretical yields. The resulting hydrolyzates, containing primarily xylose and glucose, can be fermented to ethanol or other chemicals. The acid can be recovered for reuse by solvent extraction. The sugar concentration can be increased by using high solids reactions with acid recycle. Continuous fermentation of the hydrolyzates can be achieved in an hour or less in an immobilized cell column. The capital cost for a process to produce 20 million gallons of ethanol is estimated to be \$35 million. The pre-tax profit from this facility is sufficient to encourage commercialization.

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Table 1. Municipal Solid Waste Composition  
(Weight Percent as Discarded)

<u>Category</u>	<u>Summer</u>	<u>Fall</u>	<u>Winter</u>	<u>Spring</u>	<u>Average</u>
Paper	31.0	38.9	42.2	36.5	37.4
Yard Waste	27.1	6.2	0.4	14.4	13.9
Food Waste	17.1	22.7	24.1	20.8	20.0
Glass	7.5	9.6	10.2	8.8	9.8
Metal	7.0	9.1	9.7	8.2	8.4
Wood	2.6	3.4	3.6	3.1	3.1
Textiles	1.8	2.5	2.7	2.2	2.2
Leather & Rubber	1.1	1.4	1.5	1.2	1.2
Plastics	1.1	1.2	1.4	1.1	1.4
Miscellaneous	3.1	4.0	4.2	3.7	3.4

Table 2. The Composition of Selected Biomass Materials

<u>Material</u>	<u>Percent Dry Weight of Material</u>		
	<u>Hemicellulose</u>	<u>Cellulose</u>	<u>Lignin</u>
Tanbark Oak	19.6	44.8	24.8
Corn Stover	28.1	36.5	10.4
Red Clover Hay	20.6	36.7	15.1
Bagasse	20.4	41.3	14.9
Oat Hulls	20.5	33.7	13.5
Newspaper	16.0	61.0	21.0
Processed MSW	25.0	47.0	12.0

Table 3. MSW Acid Hydrolyzates

	<u>Concentration</u> <u>g/L</u>	<u>Yield</u> <u>g/100g</u>
Prehydrolyzate		
Xylose	9.5	8.0
Glucose	18.5	16.0
Hydrolyzate		
Xylose	0.0	0.0
Glucose	67.8	44.0
Combined		
Xylose		8.0
Glucose		60.0



Table 4. Hydrolyzate Fermentation to Ethanol  
Percent Sugar Utilization

Fermentation Time (hrs)	Hydrolyzate			With Yeast Extract
	Amino Acids	With Vitamins and $\text{NH}_4(\text{PO}_4)$	Amino Acids and $\text{NH}_4(\text{PO}_4)$	
16	15.9	21.9	27.3	97.5
23	19.3	24.9	35.8	97.5

Table 5. Economics of 20 Million Gallon Per Year  
Ethanol Facility

A. Capital Cost

	<u>Million \$</u>
Feedstock Preparation	3.0
Hydrolysis	5.0
Acid Recovery	8.5
Fermentation & Purification	8.0
Utilities/Offsites	6.5
Engineering	<u>4.0</u>
	35.0

B. Operating Cost

	<u>Million \$/yr</u>	<u>\$/gal</u>
MSW	-	-
Utilities	1.5	0.08
Chemicals	1.9	0.09
Labor	2.5	0.13
Fixed Charges		
Maintenance (4%)	1.4	0.07
Depreciation (10%)	3.5	0.18
Taxes & Insurance (2%)	0.7	0.02
Pre-tax Profit (53%)	<u>18.5</u>	<u>0.93</u>
	\$30.0	\$1.50/gal

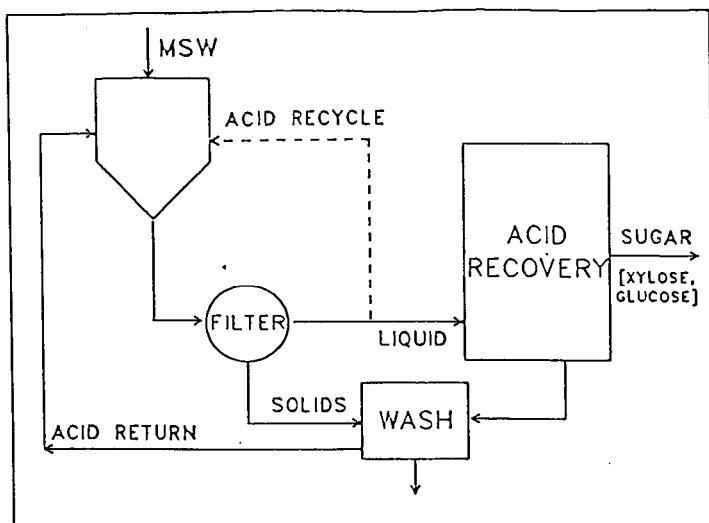


Figure 1. Schematic of Acid Hydrolysis Process

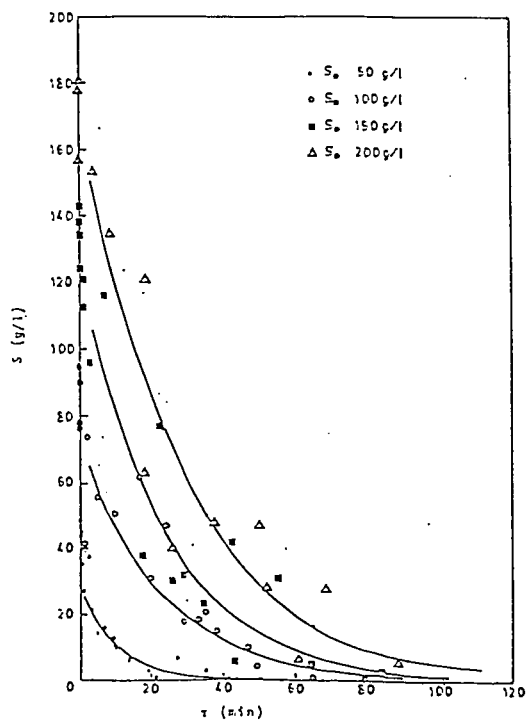


Figure 2. Glucose Profile in the ICR

## CLEAN ENERGY FROM MUNICIPAL WASTE

" The environmental advantages of the controlled combustion of municipal wastes as sources of energy".

Francis J. Cashin, D Eng. PE  
Alfred J. Angiola, PE  
Cashin Associates, PC  
255 Executive Drive  
Plainview, NY 11803-1707

Keywords: THERM (100,000 BTU's); TPD (Tons of Refuse per Day); SSRDF (Source-Separated Refuse Derived Fuels)

### ABSTRACT

This paper reviews the incinerator technology commonly employed in large municipalities prior to 1970 (the introduction of EPA regulation; and, more specifically the Clean Air Act of 1971); then, revisits the same technology as it could be applied in the 1990's, but with...an environmentally aware public, a vastly modified waste stream, the effects of recycling, controlled collection procedures, and the latest technology (being developed and/or imported from Europe).

In so doing, the review addresses: solid waste incineration prior to regulation (pre-1970); the experiences in introducing regulation (1970-1990); and, the significant environmental advantages in applying the latest knowledge, methodology, and technology to the reduction of municipal wastes by combustion, producing energies with a minimum adverse impact on the environment.

The delicate balances among the exposures (air, groundwater, land misuse), factors not properly addressed in the early stages of environmental control implementation are analyzed; and, scenarios are developed showing the overall environmental advantages when a portion of (up to 10-15%) solid waste as a fuel, replaces fossil fuels as a basic source.

### PRECIS

The accumulation of solid wastes and the disposal of same had evolved into fairly well established procedures by the 1960's. In most of the highly developed countries of the world (Western Europe, North America, and the Pacific rim) solid waste was collected and disposed of under controlled conditions. Actually, population density determined the options to be selected by the local communities.

Except to when collection procedures affect the disposal system (such as in recycling), said procedures will not be developed hereinafter. Accordingly, the emphasis will be in the disposal of solid wastes in areas of the denser populations. This will represent an estimated 90% of the solid waste of approximately 90% of the populations. The comparison of these disposal procedures of this era (prior 1970) in the United States, will be developed,

herein, using that section of Long Island not of New York City (except for the Far Rockaway area of Queens). This area coincides with the area served by the Long Island Lighting Company (LILCO), for which there is considerable statistical data available; essentially, the United States Bureau of Labor Statistics Nassau-Suffolk reporting area.'

#### INCINERATION TECHNOLOGY - PRIOR 1970

In the 1960's, the incineration of solid wastes was being developed into a fairly sophisticated technology. The concepts being introduced included:

- a. Continuously fed furnaces were replacing batch fed furnaces.
- b. Systems for controlling combustion air at the grates, in the ignition chamber, and in the combustion chamber... were evolving.
- c. Equipment effectuating complete combustion and removing particulate from the flue-gases were being installed (electrostatic precipitators).
- d. Six major companies who were supplying grate systems/furnaces, all of whom were active in further development/improvement of their systems.
- e. The American Society of Mechanical Engineers established a section, "The Incineration Committee" later to be made a division, until through mesne titles, it is referred to today as the "ASME WASTE PROCESSING DIVISION". This division started to set standards for destructive distillations of solid wastes, write codes for operation, and develop courses/manuals for "Incinerator Operations" and later "Incinerator Maintenance."
- f. As a result of the ASME (see 5 above) the first criteria for flue gas (air) and ground-water pollution control were established in the 1960's; and, more important, functional requirements for these controls were developed.
- g. The first real effective measure for flue gas (air) control and quench water (waste water) control were being field tested on operating incinerators.
- h. It is interesting to note: Several systems for energy recovery were developed and actually installed on large municipal incinerators (Town of Hempstead and Town of Oyster Bay). These systems worked well, but their use was discontinued because they were not economically feasible. The extra cost for the operation and maintenance could not be justified, when electric power was being generated from \$0.06 per gallon fuels in very efficient power plants. Only when the cost of utility fuels exceeded ten times that amount did energy recovery from solid waste (a clean fuel) become attractive.

The history of incineration in the United States for this period is well chronicled in the "Proceedings" of the Incinerator Conferences of the American Society of Mechanical Engineers (ASME) of 1964, 1966, 1968, 1970, and 1972<sup>2</sup>. Basically, all the major cities and suburban areas had either built or were under contract to build large incinerators. The typical plants were 500 tons per day (TPD) usually with two or more processing lines of 150, 200, or 250 TPD with a common tipping area and a common stack; many disposal facilities consisted of two 500 TPD plants. In the larger cities (typically New York, Chicago, Philadelphia) even larger furnaces and plants were built. Each new plant, usually employed the latest technology with the generation cycle at roughly five-years, and furnace replacement scheduled in on approximately 20-year cycle. The natural evolution of incinerator technology was in place.

It was during that period that the public was awakening to the environmental concerns resulting from energy conversions. However, the operators, designers, and manufacturers of incineration plants were already working on these environmental problems and several techniques for flue-gas cleansing and waste water recycling were being tested at new and existing incinerator plants. These environmental programs included:

- i. Electrostatic precipitators for removing particulate in flue-gas.
- j. Scrubbers for removing particulate in flue-gas and for partially absorbing certain of the undesirable gas products such as SO<sub>2</sub> and NO<sub>x</sub>'s.
- k. Setting ponds and filter systems which would permit the recycling of flue-gas contaminates water (acetic) and ash quenching water (basic).
- l. Analyses of incinerator residue to establish standards for contaminates such as heavy metals and hazardous non-metallic compounds.
- m. Studies of air dispersion patterns from stack emissions of flue-gases.

These industry wide programs of voluntary, industry-supported development and research was aborted circa 1970, upon the introduction of Federal Government regulations/controls. In developing these new regulations, and later controls, the draftsmen almost completely ignored the wealth of knowledge and experience already accumulated. This literally short-circuited all the private sector efforts. These newly ordained "experts" began programs of enforcement by federal, state, and local governmental regulating authorities newly created for this purpose. The result was devastating; and, is discussed further herinafter.

#### EMBRACING ENVIRONMENTAL REGULATION 1970 TO 1990

Once the Environmental Protection Agency was created and began trying to get a handle in environmental concerns, the programs for processing, and improving upon the processing, of solid wastes suffered greatly. Unfortunately, the original appointees (many of whom were attorneys and/or not technically trained professionals) to the higher positions in of these new regulatory agencies were almost completely unknowledgeable in environmental considerations; and, lacked the experience in setting-up standards and organizing for the regulation of same. This was disastrous to the solid waste processing industry. Segments of the environmental problems were regulated without regards to the overall environmental impacts. The Air Quality Act of 1971 epitomizes this. Standards were promulgated for air quality which were arbitrarily applied and thus adversely impacted the overall environmental quality. They were standards for which neither time for enforcement or even need for same was properly addressed.

One of the reasons for enforcing the air quality of incinerators had such high priority is that incinerators had no constituency while the total adverse effect of solid waste burning was probably less than two percent (and that adverse effect was particulate which is admittedly undesirable by not an noxious as the sulfates, nitrates, chlorocarbons, etc. of the other polluters). Regulations were enforced that had the effect of systematically closing down all incinerators, because of the (then considered) excessive costs of installing (as yet unproven) air pollution control equipage.

As a result of these actions of the regulatorys, not only were operating incinerators closed, but the several companies developing incinerator technology and building incinerators went out of the business and most of the scientists, engineers, and technologists turned to other fields of endeavor. This was unfortunate because the real causes of air quality diminuation in 1970 were:

Automobile.....	62%
Industry.....	17%
Utilities.....	16%
All other*.....	5%
*(Including incinerators).....(±2%)	
-----	
Total.....	100%

A whole new group took over the solid waste processing industry. Engineers were replaced by attorneys and financial consultants as the solving of the solid waste problem was explored by many entities including: the giants of American industry, financiers supporting (suggested but untested) technologies, and federal and state grants to test new technologies. During this period, these newly ordained experts suddenly discovered "Resource Recovery" (just as other name for incineration) and a series of pilgrimages were made to study "European technology." Actually, "European technology" was nothing more than advances on the same 1960's technology the development of which had not been interrupted by the actions of regulating authorities. As a result of this, several European countries have transferred their technology to the United States as part of their corporate structure, in partnership with or by license to United States companies.

The European countries did have an advantage in that the resource recovery (hot-water or steam) technology was much further developed in Europe. This was largely because of the relatively high cost of fossil fuel (particularly oil) in Europe, which was anywhere from five to ten times the cost American utilities were paying for low grade fuels.

While the incineration industry was completely disrupted by regulation commencing circa 1970, there were several developments which inure to the overall improvement of the technology particularly with respect to public awareness, establishment of true values, and pre-processing standards such as source separation, mandated soft-drink containers deposits, and recycling systems all of which have made possible:

- n. A significant reduction in the non-combustibles in the waste-stream, thereby decreasing the bulk handled during processing and reducing significantly the volume and weight of the (contaminated) residue by approximately 10%.
- o. The separation of yard wastes remain both surface and combined waters and reduces the heterogenous nature of the solid waste stream making it easier to process.
- p. The reduction in non-combustibles as increases in the heat value per pound (not the overall heat values) of the waste stream up to 20%.
- q. The collecting, storing, and forwarding of solid waste in disposable plastic bags reduces significantly the amount of surface water contaminating the waste stream. When equal parts of water (by weight) are added to the solid waste stream, the result is a significant reduction in the net heating value:

### The Effect of Water in Solid Waste Combustion

72 degrees F to 212 degrees F.....	-150 BTU/lb
212 degrees F (water) to 212 degrees F (steam).....	-970 BTU/lb
212 degrees F (steam) to 2,212 degrees F (superheat).....	-1,000 BTU/lb
Total.....	-2,020 BTU/lb
1 lb solid waste.....	5,000 BTU/lb
1 lb water.....	-2,020 BTU/lb
Net heating value/lb.....	2,980 BTU/lb

Regulation, education, and economics have significantly altered the factors for evaluating solid waste as a viable fuel. The remaining waste after this separation of rubble and yard wastes and the recycling of paper, plastics, glass, metal containers and certain hazardous fuel is Source Separated Refuse Derived Fuel SSRDF (not to be confused with the RDF product of mechanically processed solid waste streams). The SSRDF has there main components:

Waste Stream Analyses - Abstracted from Town of Oyster Bay Solid Waste Management Plan - November 1990 by Cashin Associates P.C. (Corrected for rubble removal)<sup>3</sup>

Products (Combined)	Pre-Recycle 1984	Post-Recycle 1990
Papers	41.4	42.5
Glass	6.5	3.0
Metals	5.7	6.3
Plastics	8.0	8.0
Rubber	0.3	0.3
Textiles	1.7	3.6
Wood	5.4	8.5
Food	9.3	4.7
Yard	13.8	10.5
Inorganic	4.3	5.3
Miscellaneous	3.6	1.6
	100.0	100.0

This SSRDF has a calculated heat value of approximate 5,000 BTU's per pound plus or minus 10%, which compares with other non-renewal fuels as follows:

TYPE OF FUEL <sup>4</sup>	HEATING BTU/lb	VALUE Therms/Ton	Equivalent Bulk Unit
Natural Gas	22,000	440	41.08 MCF
Fuel Oil NO2	19,430	389	6.61 BBL
Fuel Oil NO6	18,300	366	6.10 BBL
Coal	15,500	308	1 TON
Coal	13,000	260	1 TON
Coke	11,670	233	1 TON
Pulp	6,700	134	1 TON
Begasse	4,000	80	1 TON
SSRDF	5,000	100	1 TON
Paper/Cardboard	6,500	130	1 TON
Plastic-Average	16,000	320	1 TON

## RESOURCE RECOVERY TECHNOLOGY AFTER 1990

In order to bring into focus the potential energy available in solid waste, a comparison of the renewable energies shows:

### Solar Energy Annually Available To The World From Reusable Sources<sup>5</sup>

<u>SOURCE</u>	<u>BILLIONS OF THERMS</u>
Solar collectors	433,000
Waterfall	9,000
Land Vegetation	1,600
Tropical Waters	500
Wind	50
Heat Pumps	50
Solid Waste (United States)	23.62
Solid Waste (Nassau/Suffolk)	0.23

### All Types of Energy Sources Used By LILCO For The Year-1990<sup>6</sup>

Fuel Oil	1.01	56%
Natural Gas	0.36	20%
Nuclear Power	0.07	4%
Purchased	0.36	20%
Total.....	1.80	100%

With the above statistics, a program for energy recoverable from solid waste can be evaluated. Approximately ten percent of the total electrical energy for this designated area (LILCO) could be produced from the solid waste generated therein. Looking at this possible alternative and at the changes in conditions brought about in the twenty years (1970-1990) by the introduction of regulations and environmental consciousness has produced many benefits, which will make solid waste more feasible and more attractive as an annually renewable energy source.

In producing energy, the most important considerations are economic and environmental, which complement one another. When comparing SSRDF with the energy sources, it is most likely to replace, SSRDF has the advantage:

<u>CONSIDERATION</u>	<u>ECONOMIC COST/DECA THERM</u>	<u>ENVIRONMENTAL Sulfur Content</u>
Fuel Type	\$	%
Fuel Oil	\$2.18	1.0
Nature Gas	1.80	Trace
Nuclear Power	0.98	0
SSRDF		Trace



The costs given for alternate fuels are from LILCO and are the average 1990 costs. The nuclear power is produced by facilities in which LILCO is partner.

SSRDF has essentially no cost as the cost of disposal is eliminated, if the SSRDF is used as a fuel for energy conversion. However, the costs of set conversion are higher than the costs for an equivalent amount of other fuels generated in the larger more efficient utility power plants.

#### THE FUTURE OF RESOURCE CONTROL - CIRCA 2000

As a result of the factors mentioned above, between 1970 and 1990, the control of solid waste processing has shifted in part from the ultimate disposer (landfill manager/incinerator plant operator) to the consumer, who has been taking more and more responsibilities for recycling.

As the environmental consciousness continues to evolve and the general knowledge of the public increases, the control of solid waste processing will gradually shift to the generators. A series of controls are being enacted, considered, and/or planned by Federal/State Agencies to:

- t. Further expand beverage container control to all parts the country.
- u. Reduce or eliminate undesirable compounds from packaging and expendable products (Fluorocarbons, etc.).
- v. Require more reusable containers for consumer product delivery.
- w. Reduce excess packaging; particularly, when the solid packaging is several times the bulk of the product delivered.
- x. Require disposable products and packaging, when not readily biodegradable to be safely reducible by combustion.
- y. Provide recycling systems for hazardous consumables (chemicals, batteries, oil wastes, etc.).
- z. Containers for liquids will be regulated as to size, shape, type of label, and all types of materials used.

The solid waste problem will never be completely resolved, but slowly over the next twenty year (by 2010), the waste stream in the country will be controlled by the cooperation of the producers, consumers, and disposers.

#### SUMMARY

If the experiences of the past twenty years are carefully reviewed, a program for solving the ecological exposures in processing our waste stream can be resolved, unfortunately, in recent years, well intentioned environmentalists, supported by opportunist politicians, have skewed the public's understanding of this environmental problem.

For the past several years the public has been exposed to perceptions, not facts. It is time for the technologically trained scientists, engineers, and educators to speak out on all the environmental issues and put these issues in their proper perspective.

#### FOOTNOTES

1The Long Island Lighting Company's (LILCO) operating area essentially coincides with the United States Bureau of Labor Statistics reporting area of Nassau and Suffolk Counties in New York State. This area has a diverse nature with a population of 2.3 million, which is approximately one percent of the population of the United States. This area is uniquely situated on an island surrounded by water on three sides and New York City to the west. This assures control of the solid waste stream, which is impacted neither by the importation of foreign wastes, nor the export of locally generated wastes, except as part of controlled disposal programs of local municipalities).

2The American Society of Mechanical Engineers (ASME) commenced holding biennial conferences in 1964, all of which have been published in these "Proceedings", which are available in local technical libraries or the Engineering Library of the Engineering Building 345 East 47th Street, New York, NY 10011; or, may be purchased (not all years available) from ASME, 345 East 47th Street, New York, NY 10011. These proceedings are chronology of the then state-of-the-art, the operating data, and program for research and development...of the Incinerator/Waste Processing Industry.

3The Town of Oyster Bay Solid Waste Management Plan - November 1990 by Cashin Associates P.C., 255 Executive Drive, Plainview, New York 11803. Contains a summary of a series of solid waste analyses made by CASHIN ASSOCIATES P.C. from which these data were abstracted.

4Steam/its generation and use-Babcock & Wilcox, 161 East 42nd Street, New York, NY 10017.

5Energy Sources - The Wealth of the World, Ayres and Scarlott - Mc Graw-Hill, 1221 Avenue Americas, New York, NY 10027.

6Long Island Lighting Company - 1990 - Annual Report and supporting documents. LILCO, 175 Old Country Road, Hicksville, NY 11801.